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Investigation of the Fatigue and Short-Term Mechanical Properties of 13% Chromium Steel and Titanium Alloys after Welding or Treatment with High-Frequency Currents as Applied to Steam-Turbine Blades

F. G. Gonserovskii[a], V. I. Nikitin[a], V. M. Silevich[a], and O. N. Simin[b]

[a] *Central Boiler-Turbine Institute Research and Production Association (NPO TsKTI), Atamanskaya ul. 3/6, St. Petersburg, 191167 Russia*

[b] *Leningrad Metal Works (LMZ), OAO Silovye Mashiny, Sverdlovskaya nab. 18, St. Petersburg, 195009 Russia*

Abstract—We present the results of a study on comparing the structural strength of rotor blades made of stainless 13% chromium steels for their design versions in which wear-resistant straps made of cast VZK stellite are soldered or welded on the blade inlet edges. It is shown that treatment of VT6 alloy with high-frequency currents increases the endurance limit of the zone subjected to strengthening and makes the alloy more resistant to erosion. The worn blades of a 48-T4 titanium alloy repaired with the use of welding technologies have operational characteristics at least as good as those of newly manufactured ones.

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Premature selective local destruction of certain subassemblies and parts of various machines and units frequently occurs during their operation. So far as articles produced by the industry of constructing power machinery and equipment are concerned, local wear is frequently observed in narrow areas of the edges of rotor blades and guide vanes of steam turbines at thermal and nuclear power stations due to droplet-impingement erosion or the effect of solid particles (e.g., scale). Fretting corrosion, as well as the slit erosion of metals, develops in some cases. This causes the local dimensions of blades to alter, which may lead to the occurrence of pre-emergency situations in which the turbine has to be shut down for the urgent repair. An unscheduled outage of a turbine and its repair result in considerable lumped amounts of electric energy underproduced, the negative consequences of which are especially sensitive in the case of large turbines, e.g., those with capacities of 300–800 MW.

Apart from the fact that a change (reduction) in local dimensions is a real precursor of accidents, a wear of the feather of last-stage low-pressure steam-turbine rotor blades causes their windage to decrease. As a result, part of the steam constantly passes through the flow path of cylinders without making any work. This, in turn, results in a lower output generated by the working stages and in a poorer economic efficiency of the turbine [1]. This phenomenon is observed to one degree or another in many turbines no matter what metals are used as material for making their blades, be it 13% stainless chromium steels or 48-T4, TS5, or VT6-grade titanium alloys. Underproduction of electric power is usually compensated for by increased consumption of fuel (fuel oil, coal, gas, or uranium), without concern for the environmental consequences for the surrounding medium. Therefore, monitoring and restoring the dimensions of turbine blades, which change during long-term operation, should be considered a very topical problem.

To prevent or minimize the occurrence of situations like those described above, e.g., with rotor blades, TsKTI specialists have developed welding technologies that allow the worn zones of these blades to be restored at power stations or at factories [2]. Figure 1 shows how such blades look after they have been restored by means of surfacing or welding an insert to the feather, the material of which may be an erosion-resistant metal. Such methods are used for repairing blades made of 13% chromium steels, as well as of low-strength and plastic titanium α-alloys. As an example, we can mention blades made of 48-T4 titanium that were restored by means of surfacing in 1984 after they had been in operation for about 85000 h and operated without giving rise to any criticism until 2004. In addition, they underwent 800 starting operations and two failures of the stage that were not related to the welding. At present, these blades have been withdrawn from operation in connection with the overhaul of the entire low-pressure rotor. The operability of the blades made of these titanium alloys that passed repair by surfacing is commensurable with that assigned by the manufacturer for newly fabricated ones.

The investigations of the fatigue strength of the welded joints we carried out on flat model samples, as well as on standard full-scale steel blades, according to the repair schemes shown in Fig. 1, have shown that the

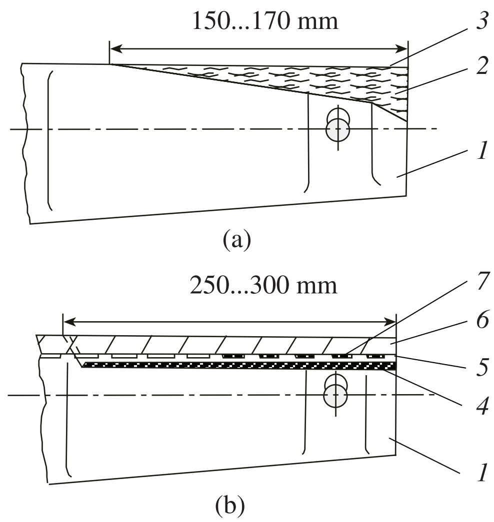

Fig. 1. The view of rotor blades after they were restored by (a) surfacing and (b) welding. (*1*) Worn feather, (*2*) metal restoring the size of the chord, (*3*) erosion-resistant metal, (*4*) butt weld, (*5*) insert, (*6*) stellite straps, and (*7*) welded seams.

use of welding technologies does not lead to an inadmissible reduction in their working ability as compared to the method according to which strengthening stellite straps are soldered, an approach the industry's manufacturing plants have practiced for a long time. For example, repair to the blades manufactured at the Turbine Engine Works (TMZ) carried out according to the TsKTI technology (which includes operations on restoring the feather chord to the design dimensions and welding a protective belt of anti-erosion straps made of cast VZK stellite to the feather) results in making them twice as durable as those repaired by soldering protective straps on them (Table 1). However, the conditions necessary for carrying out repair work cannot always be provided at power stations, since the proper quality of welded joints in chromium steels, and all the more so of welded joints in titanium alloys, can only be obtained if the welding operations are carried out in pure and dry surrounding atmosphere and without drafts, all sorts of pollutions, etc. In addition, the fatigue strength limit of the welded joints obtained when local damages on titanium blades are repaired by surfacing or welding is at a level of 180 MPa, which is not always in line with the designer's requirements. This is especially unacceptable when the conditions under which blades in large-capacity turbines operate generate the need of using high-strength titanium alloys, e.g., a VT6 alloy with an ultimate strength of 950–1000 MPa and a fatigue strength limit of not lower than 410–450 MPa.

Table 1. Fatigue strength values of rotor blades

Rotor blades	Working length, mm	σ_{-1}, MPa	Manufacturer
Manufactured at a factory, with soldered protective straps	665	40	TMZ
	940	40	TMZ
	665	100	LMZ
	960	100	LMZ
After repair according to TsKTI technology under the conditions of power stations	665	90	TMZ
	940	90	TMZ
	665*	100	LMZ
	960**	97	LMZ

Notes: * Full-scale model.
** Fragment of a 700-mm-long feather.

Since attempts to achieve such results on titanium with the use of welding technologies have not hitherto met with success, a decision was made at the TsKTI according to which the strength of severely local areas of the inlet edge of a blade made of VT6 alloy severely being damaged is increased during the manufacture by locally heating them with high-frequency currents followed by quenching in water. Upon passing quenching of this sort followed by tempering, such sections acquire a strength of from 1230 to 1330 MPa; as a result, their resistance to drop-impingement erosion, as has been demonstrated by investigations and field experience with operation of turbines, increases at least by 2.7–3.0 times as compared with that of the blade metal designed for a structural strength of 950–1000 MPa. The local (functional) strength is achieved in feather metal area at the inlet edge with a width of 20–25 and 400–450 mm in length by calcinating it over the entire thickness of the feather.

Another factor essential for the proper working ability of blades made of VT6 alloy treated using the above method is the fatigue strength limit, which, according to the designer's requirement, must be not lower than that of the blade material calculated from the conditions of its structural strength, i.e., within the range of 400–450 MPa.

The main objective of this study was to determine the fatigue strength limits of the considered feather areas heated by high-frequency currents to temperatures of 1000–1100°C (the first series of ten samples) and in the transition part from the zone affected by high temperature to the region with room temperature, within which inadmissible reduction in the strength of the blade feather can be expected (the second series of ten samples).

The first series of fatigue tests was carried out at the TsKTI with the use of cantilever samples fabricated of VT6 alloy rods 24.5 mm in diameter, the chemical composition of which is given in Table 2, and the initial mechanical properties of this alloy are listed in Table 3. The mechanical characteristics of the initial material were in line with the requirements of OST (Industry Standard) 1-90002-86 (Suppllement 15) for rotor blades.

Table 2. Chemical composition of VT6 alloy, wt %

Composition	Al	V	Zr	Si	Fe	C	O_2	N_2	H	Σ*	Cu + Mn	Cu + Ni
In accordance with OST (Industry Standard) 1-90002-86 (Supplement 15)	5.3…6.8	3.5…5.3	≤0.30	≤0.10	≤0.66	≤0.10	≤0.20	≤0.060	≤0.005	≤0.3	≤0.15	≤0.10
Actual	6.5	4.9	0.02	0.044	0.23	0.01	0.188	0.04	0.003	0.241	0.038	0.04

* Total sum of the implantation impurities $O_2 + N_2 + H$.

The test portion of the blanks for these samples with a diameter of 10 mm was subjected to cyclic heating at a temperature of 850–1075°C. The total time for which the blanks were held at the maximum temperature was equal to 15–18 s. After that, the blanks were immediately cooled in cold water; this quenching operation was followed by tempering at 550°C with holding for 2 h. Subsequently, samples with a test portion 8 mm in diameter were made of them. The fatigue tests of these cantilever samples were carried out under a symmetrical alternating load on the basis of 2×10^7 cycles on a testing machine, on which they were rotated at a speed of 3000 rpm. The results of experiments on determining the true fatigue strength limit of the metal in the strengthened zone, due to which the rotor blade has substantially higher resistance to erosion, are shown in Fig. 2.

The fatigue strength curve obtained from the tests of ten samples on the basis of 2×10^7 cycles is shown by dots on the graph $\sigma_{max} = f(N)$, where N is the number of cycles. It can be seen that the fatigue curve has a descending branch, which transforms into horizontal section at $\sigma_{max} \approx 505$ MPa. This transition turned out to be extremely sharp, because the fracture of samples is observed only to the number of cycles $N = 1.1 \times 10^5$. It is noted that the treatment of VT6 alloy with high-frequency currents causes its endurance limit to increase from 410 MPa in its usual (construction) state in accordance with the requirements of OST (Industry Standard) 1-90002-86 (Supplement 15) to 510 MPa.

As regards the question about the strength and endurance of the transition zone between the inlet edge section strengthened by quenching at 1000–1100°C and the base metal that had not been subjected to heating by high-frequency currents, we intended to find an answer to this question from fatigue tests of the second series of samples (Fig. 3). The quenching operation was carried out in the middle part of each blank with a view to obtaining five zones of thermal state in a completely treated sample: one quenched zone, two transition zones, and two zones with the initial state (near the fillets). When a sample is loaded in accordance with the four-point scheme, all these zones experience a constant moment of force with the same stresses in the rotating sample.

The distribution of microhardness over the sample's test portion at a load of 9.8 N is shown in Fig. 4. It can be seen that the maximum hardness of 390–400 HV is observed in the middle of the sample's test portion in the spot where the high-frequency current inductor's loop is situated when the blade inlet edge is heated for hardening. Two transitional zones each 20–25 mm long are situated on both sides of the quenched zone; the hardness in these zones reduces toward the fillets to the initial level of 320 HV. No abrupt reduction in the hardness values has been found.

Since there were doubts regarding the occurrence of the areas of metal with an inadmissible level of weakening after the treatment of a feather edge with high-frequency currents, during which a temperature difference from 1100 to 40°C occurred at a distance of 30–40 mm, we carried out tests of the mechanical properties of the metal subjected to the effect of these temperatures. For this purpose, Gagarin and impact-test samples were fabricated of VT6 alloy, which were quenched in water after heating them by high-frequency currents and in a furnace at temperatures of 1075, 975, and 850°C (for checking the results), tempered in a typical thermal furnace at temperatures of 550, 580, 600, and 620°C, and tested.

The results of mechanical tests indicate that the metal became less strong only after it had been subjected to treatment at 850°C (it was held at this temperature for 2 h), but the strength and ductility characteristics of the metal corresponded to the similar parameters of the tested section of VT6 alloy in the initial state or outperformed them (see Table 3). In addition, it has been demonstrated that the tensile ultimate strength of the VT6 alloy sections quenched by high-frequency

Table 3. Mechanical characteristics of the initial VT6 material

Characteristics	$\sigma_{0.2}$, MPa	σ_v, MPa	δ, %	φ, %	Impact toughness (KCU), J/cm^2
In accordance with OST (Industry Standard) 1-90002-86 (Supplement 15)	≥804	≥902	≥10	≥25	≥34.3
Actual (for three samples)	–	1002	14.4	47.0	43.1
	–	1024	13.2	44.3	42.1
	–	1014	12.8	46.7	40.2

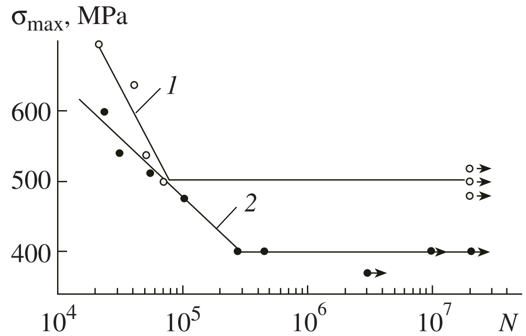

Fig. 2. Fatigue strength limits of the samples made of VT6 alloy after heating by high-frequency currents and cooling in water followed by tempering at 550°C and holding for 2 h in a usual furnace. (*1*) Strengthened zone with high resistance to drop-impingement erosion at the inlet edge of a steam-turbine blade feather (the zone is singled out in pure form); (*2*) the totality of three zones: a high-strength one, a transition to the metal with the design strength, and a zone which not subjected to heating higher than 200°C during the treatment of the feather edge by high-frequency currents.

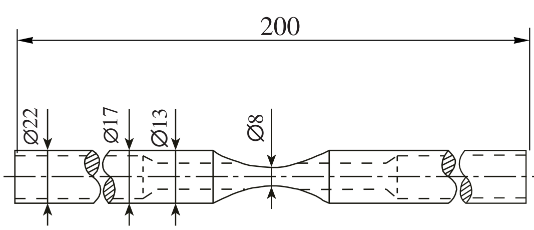

Fig. 3. Blank made of VT6 alloy for being treated by high-frequency currents (shown by solid lines), and the sample made of it (shown by dashed lines) for carrying out fatigue tests of its test portion.

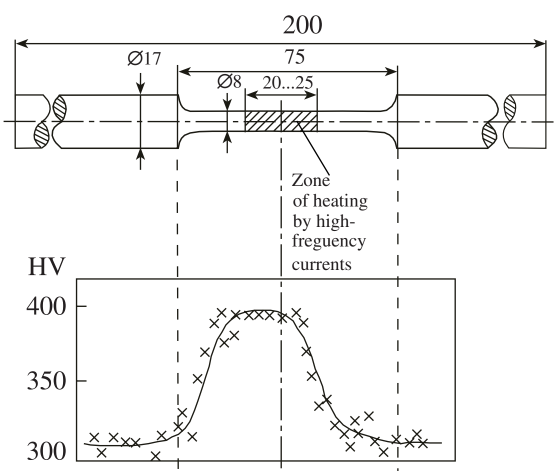

Fig. 4. Distribution of hardness along the sample test portion during fatigue tests (after it was treated with high-frequency currents in accordance with the standard schedule for rotor blade feathers; the hardness was measured along the sample axis).

currents increases to 1303 Mpa and the hardness increases to 435–460 HV, whereas the relative elongation and contraction decrease to 5.7 and 9.9%, respectively, with an impact toughness of 2.35 J/cm^2. The subsequent tempering of the quenched samples at a temperature of 570–580°C for 2 h (for reducing the residual thermal tensile stresses to 4.6 MPa) decreases their tensile ultimate strength to 1205 MPa; hardness, to 390–400 HV; and relative elongation, to 4.7%, while increasing the relative contraction to 13%.

Thus, a jump of the strength and ductility properties, as well as a corresponding change in the structural states from the $\alpha + \beta$-phase (the initial state of VT6 alloy) to α'-phase with partially ageing it during the tempering at 570–580°C (for 2 h), is observed in the considered section of the future blade treated by high-frequency currents. We had to determine what influence these two factors will exert on the fatigue strength.

The samples with the aforesaid transition zones were tested at the material strength laboratory of the Politekhtest testing center of St. Petersburg State Polytechnic University. The tests were carried out on the serial MUI-6000 testing machine, during which the samples rotating at a speed of 2750 rpm were subjected to a bending load in accordance with the four-point loading scheme in conformity with the requirements of GOST (State Standard) 25.502-79.

During the tests, six samples failed (see Fig. 2, curve *2*), two samples withstood 10^7 loading cycles, and one sample withstood 2×10^7 cycles. One sample, which was subjected to σ_{max} = 395 MPa and passed 3×10^6 cycles, was withdrawn from the tests, since it is unrealistic that failure may occur before 10^7 loading cycles. All failures occurred at σ_{max} > 410 MPa. This value corresponds to the fatigue strength limit σ_{-1} of VT6 alloy. The fact that no failures occurred in 12 transition zones (two zones per each of the six failed specimens) indicates that no inadmissible loss of metal strength occurred, which, supposedly, could accompany the strengthening of the blade edges by heating with high-frequency currents.

Posttest examination of the samples has shown that the failed sections are located at the maximum distance from the zone of treatment with high-frequency currents—almost at the boundary between the sample's cylindrical part and the fillet—and a tiny step is observed at the failed section of two samples, pointing to the fact that the failure develops over the basic metal not heated by high-frequency currents. No failures were found in the transition zones. The fatigue characteristics of the metal in these zones are at least as good as those of the base metal that was not subjected to heating with high-frequency currents [3].

That the endurance limit of the zone strengthened by high-frequency currents increased from 410 to 505 MPa may be explained by the formation of quenching phase α', the strength of which is 20–25% higher than that of the base metal subjected to standard thermal treatment.

CONCLUSIONS

(1) Steam-turbine blades worn due to erosion may be restored at site using welding technologies. The use of these technologies for titanium alloys has certain limitations, since the metal of welded joints or surfaced metal has lower values of the endurance limit due to the welding defects (pores) that are inherent in the metal of these joints. However, the practical experience gained during 20 years of the operation of the entire runner of a K-300-240 turbine (with 100 blades) does not confirm this anxiety.

(2) The treatment of the blade feather sections prone to intense wear due to drop-impingement erosion by heating them with high-frequency currents followed by quenching in water allows their resistance to erosion to be increased by a factor of 2.7–3.0 as compared with that of the blade metal not subjected to treatment with high-frequency currents. The endurance limit of the metal of such a blade does not degrade.

(3) The reduction of strength to the values $\sigma_v = 1078$ and $\sigma_{0.2} = 1156$ MPa that occurs in the transition zone between the strengthened section and the region that was not subjected to heating in the course of treating with high-frequency currents the feather of a blade made of VT6 alloy does not lead to an inadmissible reduction in the fatigue strength limit. It turns to be equal to 410 MPa, as that in the initial metal.

(4) The worn (by erosion) last-stage low-pressure 665- and 765-mm-long rotor blades made of 13% stainless chromium steels restored using the proposed welding technologies, according to which protective stellite straps are welded to the inlet edges and which have a design fatigue strength limit of 90–100 MPa, have been used in steam turbines since 1984, showing a performance in terms of this parameter at least as good as that of blades with soldered straps.

(5) The worn (by erosion) blades of a K-300-240 turbine made of 48-T4 titanium alloy restored using the welding technology according to which erosion resistant TS8 titanium alloy is surfaced on the feather edges have successfully operated in the turbine for 20 years, having operated for around 100000 h and undergone 800 starting operations, after which they were withdrawn from operation in a working state.

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